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Large excavations and their effect on displacement of land boundaries

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LARGE EXCAVATIONS AND THEIR EFFECT ON DISPLACEMENT OF LAND BOUNDARIES

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ABSTRACT: *A* study to estimate land surface movement caused by large surface excavations in sedimentary strata is presented.   In stratified or jointed strata the stress relief driven movement adjacent to large excavations can be significantly larger than expected.   High lateral stresses measured in Australia and other places around the world indicate that the ratio of horizontal to vertical stress has been particularly high at a shallow depth.   The *in situ* strata is in compression and during excavation, stress is relieved towards the opening causing strata movement.   Large excavations such as, open cut mines or highway cuttings, can initiate an extensive horizontal slide of surface layers towards the excavation.   These ground movements can be damaging to surface structures such as water storage dams and large buildings.   Based on stress measurements at shallow depths in Australian coal mines the study presented here calculates the extent of potential ground movement along the bedding surface adjacent to large excavations and provides a new prediction tool of land movement at the excavation boundary that can benefit the geotechnical practitioners in the mining industry.

INTRODUCTION

Numerous stress measurements undertaken in Australian mines and elsewhere around the world provide evidence of significant lateral stress in rock below the earth's surface.   The lateral stress appears to increase with depth and can be larger than the vertical stress.   The maximum horizontal stress is usually oriented in a specific direction depending on the geographic location and ground structure formation and its magnitude can be higher than the vertical stress.   The minor horizontal stress is oriented at $90°$ to the maximum horizontal stress.

On a large scale the faulted and bedded ground behaves as a fractured rock mass.   The continuous tectonic movement induces large horizontal stresses within the ground that are partially relieved close to the surface as the unconfined fractured rock displaces in time along the faults and other discontinuities. The amount of stress relief below the surface depends on the minimum compressive stress that provides confinement to the triaxially loaded fractured rock mass.   As the depth increases, the confining stress will increase, thereby allowing a progressively larger horizontal stress to transmit through the fractured ground.   Taking this into consideration, the maximum lateral stress at a shallow depth should be very low.   However, stress measurements indicate that there can be a considerable amount of the lateral stress locked within the strata very close to the surface.   In general, if fractures are plentiful and are oriented at a low angle to the tectonic movement, the lateral stresses would be low however, if these fractures are not present or are oriented at a high angle to the direction of ground stress, a significant proportion of the lateral stress can remain locked within the ground.   Large excavations can relieve the locked lateral stress within the surrounding strata mobilising large displacements towards the excavation that can cause damage to surrounding structures.   This effect can be magnified in sedimentary strata where failure of weak bedding planes can initiate a far reaching lateral slide of strata.

STRESS AT SHALLOW DEPTH

A number of stress measurements around the world were analysed by Mark (2010) indicating that the average lateral stress magnitude at a shallow depth may be of a significant value.   Mark's statistical analysis matched the equation $S_{Hmax}=B_0+B_1(Depth)$ to the data, where S_{Hmax} represents the maximum horizontal stress (σ_1), B_0 is an excess stress and B_1 is the gradient of lateral stress increase with depth of cover.   The excess stress is described as the lateral stress extrapolated from the data to be the near surface stress (Figure 1).   Mark estimated that the maximum lateral stress near the surface is on average about 7 MPa, however the plotted data indicate variation from 0 to 12 MPa.   The excess stress described by the linear equation serves as a prediction tool of lateral stress at a depth.   If

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considering the measured values near the surface only than the average lateral stress at the surface may not be greater than 5 to 6 MPa.

Variations of rock stiffness within the sedimentary strata beds can influence the magnitude of the measured stress and a normalisation technique is recommended to re-calculate all measured data to an average Young's Modulus of rock (Nemcik, *et al.,* 2005). Since about 70% of the earth's crust is sedimentary in composition of various stiffness, normalised stress data would increase the accuracy of the lateral stress. Figure 2 shows the measurements by Strata Control Technology (SCT) representing the pre-mining maximum lateral stress in Australian coal mines (Nemcik*, et al.,* 2006). These measurements were taken exclusively in coal measures. All measurements were normalised to the average Young's Modulus of 16 GPa of common sandstone. Despite the normalisation, there is a scatter of lateral stress magnitudes at a shallow depth probably due to orientation of structures within the strata. From the data presented in Figures 1 and 2 the maximum lateral stress close to the surface can be assumed to be approximately 5 MPa.
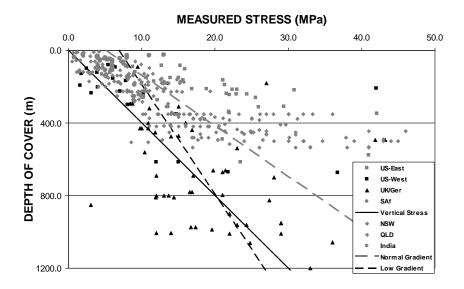

Figure 1 - The coal stress measurements data base, showing predicted ranges of stress for regions with "normal" and "low" depth gradients (Mark, 2010)
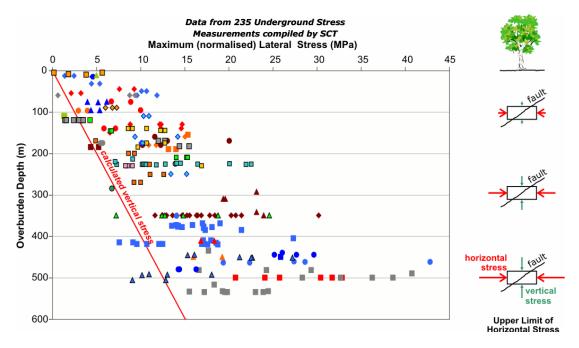

Figure 2 - Increase of pre-mining maximum horizontal stress with depth in Australian coal mines (Nemcik, *et al.,* 2006)

INFLUENCE OF THE LATERAL STRESS RELIEF ON STRATA DISPLACEMENTS IN STRATIFIED ROCK

Large surface excavations relieve the lateral stress towards the free excavated face. In an elastic rock, predictable strata displacements occur. Sedimentary rock formations that cover some 70% of the world's surface are predominantly bedded with discontinuities that are much weaker than the strength of the surrounding rock. The stress relief towards the excavation generates significant shear stresses along the bedding planes and under the right conditions, failure of the weakest bedding plane occurs and initiates displacements towards the opening (Figure 3). The slip along weak bedding planes initiate displacements that are greater than displacements in massive strata. In many cases floor failure and heave can be experienced within the excavation.
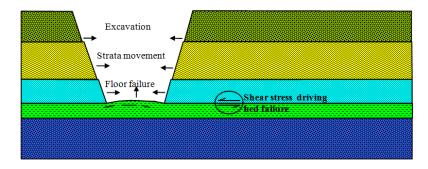

Figure 3 - Cross-section of excavated trench in laterally loaded bedded strata

CALCULATIONS OF LATERAL DISPLACEMENTS IN BEDDED STRATA ADJACENT TO LARGE EXCAVATIONS

Lateral displacement along a failed bedding plane is influenced by stress relief, strength of the bedding plane, stiffness of strata and the depth of cover. The simplified method presented here assumes a shallow vertical trench, a single weak bedding plane adjacent to the excavation and the *in situ* lateral stress σ_x. The failure mechanism is detailed in Figure 4a and 4b. Mathematical equations verified by a numerical model were used to calculate the total failure length along a single bedding plane and the lateral displacement towards the opening. Note that in this initial model the strata deformation due to the Shear Modulus of rock is not taken into consideration while for simplicity the cohesion of a weak bedding plane is also assumed to be zero.
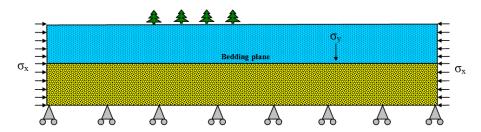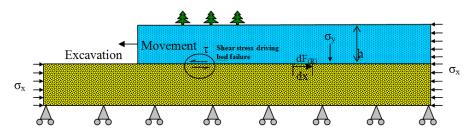

Figure 4a - Compressed strata before excavation

Figure 4b - Stress relief and movement towards the excavation

The initial analysis also assumed a single rock bed where the uniformly distributed *in situ* lateral stress σ_x is relieved into the excavation. The total length of bedding failure and the lateral displacement towards the opening are calculated as follows:

The failure along bedding plane will occur when the lateral shear along the bedding plane exceeds the bedding shear strength. This can be described in terms of forces as:

$$F_x \geq N \tan \phi + C_b \tag{1}$$

where:
F_x = *Lateral reaction force along the bedding plane induced by the lateral expansion of the rock bed above;*
N = *Normal force on bedding plane;*

ϕ_b = *Angle of friction along bedding plane and*

C_b = *Cohesion force along the bedding plane (assumed here to be zero),*
It is assumed that $C_b = c_b A_b$ *when*

c_b = *Cohesion stress along the bedding plane (assumed here to be zero);*
A_b = *Area of the bedding plane under consideration.*

The small reaction force $dF_{(R)}$ within the distance *dx* along the failed bedding plane (Figure 4b) opposes the movement of expanding strata above and can be calculated as:

$$dF_{(R)} = \gamma \ hb_z \tan \phi \ dx \tag{2}$$

Where:
$dF_{(R)}$ = *the small reaction force along the bedding within the distance dx;*
γ = *Rock density;*
ϕ = *Angle of friction along the bedding plane;*
h = *Depth above the bedding plane;*
b = *Out of plane rock bed thickness.*

The small force $dF_{(R)}$ is opposing the difference in lateral stress $d\sigma_x$ acting over the cross-sectional area *A=hb* and the distance *dx*. Note that the small force $dF_{(R)}$ is proportional to the bedding depth *(h)*, the angle of friction *(φ)* along the bedding and is opposing the lateral movement due to the stress relief above the failed plane.

The rate of lateral stress increase $d\sigma_x / dx$ from the excavation edge can be expressed as:

$$\frac{d\sigma_x}{dx} = \frac{dF_{(R)}}{bhdx} = \gamma \tan \phi \ \ or \ \ dF_{(R)} = \gamma bh \tan \phi dx$$

Therefore from the equation (2) the magnitude of lateral stress in rock above the bedding anywhere along the horizontal distance x from the excavation edge towards the end of the bedding failure can be expressed as:

$$\sigma_x = \int_0^x \gamma \tan \phi \ dx = \gamma \tan \phi \ x \tag{3}$$

Equation (3) indicates that in this particular case the magnitude of lateral stress σ_x adjacent to the excavation edge increases linearly with the constant frictional resistance along the bedding until it reaches the virgin lateral stress value ($\sigma_{xVirgin}$).

The length of the bedding failure *(L)* can be calculated from the total frictional force generated along the failed bedding plane that has to balance the opposing force generated by the lateral stress in the overburden rock equal to $hb\sigma_{xVirgin}$ at a distance *L* from the excavation face.
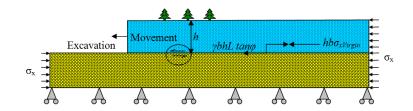

Figure 5 - Balancing forces of $hb\sigma_{xVirgin}$ **and** $\gamma hbL\tan\phi$

For static equilibrium the total frictional and driving forces must be equal.   The length of the bedding failure (*L*) can be calculated from:

$$hb\sigma_{xVirgin} = \int_0^L dF_{(R)} = \int_0^L \gamma hb \tan\phi \, dx = \gamma hb \tan\phi \, L$$

Where the total driving force

$$F_{\sigma xVirgin} = \sigma_{xVirgin} hb \quad \text{and} \quad L = \frac{\sigma_{xVirgin}}{\gamma \tan\phi} \tag{4}$$

The derived equation (4) can be used to calculate the approximate length of the single bedding plane failure.

The total lateral displacement at the excavation edge along the failed bedding plane can be calculated by integrating small displacements along the bedding.   These can be calculated from the stress relief within the overburden rock. The small displacement (*dD*) along the lateral distance *dx* can be expressed as:

$$dD = \varepsilon.dx = \frac{d\sigma_x}{E} dx$$

Where:
   ε= strain relief at the distance x;

   $d\sigma_x$ *= change in lateral stress in rock bed at distance x from excavation;*

   E= Young's Modulus of the rock bed.

The total lateral displacement (*D₀*) at the excavation can be calculated as follows:

$$D_0 = \frac{1}{E}\int_0^L (\sigma_{xVirgin} - \gamma \tan\phi \, x)dx \quad = \quad \frac{1}{E}\int_0^L (\gamma \tan\phi \, L - \gamma \tan\phi \, x)dx$$

$$= \frac{\gamma \tan\phi}{E}\left[Lx - \frac{x^2}{2} \right]_0^L = \frac{L^2 \gamma \tan\phi}{2E} \tag{5}$$

And the total displacement anywhere along the failed bedding plane is:

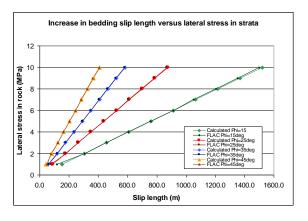$$D_x = \frac{1}{E}\int_x^L \sigma_{xVirgin} - \gamma \tan\phi \, xdx \quad = \quad \frac{\gamma \tan\phi}{E}\int_x^L (L-x)dx$$

$$= \frac{\gamma \tan\phi}{2E}\left[L^2 - 2Lx + x^2 \right] \tag{6}$$

NUMERICAL MODEL

The numerical modelling using FLAC, (Itasca 2005) was used to validate the calculations of the bedding failure. The bedding plane was simulated using the FLAC interface available to model movement along the discontinuities. The properties used in the FLAC model are given in Table 1. The calculated and modelled results of the slip length and the lateral strata displacement for various properties along the bedding plane are presented in Figures 6a and 6b. The length of the single bedding plane failure varied depending on the bed friction properties that can be very low for weak clay or mudstone deposits and larger for competent rocks such as sandstone. For bedding friction ranging from 15˚ to 45˚ and range of lateral stresses from 1 to 10 MPa the results (Figure 6a and 6b) indicate strata displacements from very small up to 480 mm at the excavation edge with slip length along the bedding ranging from 40 m to 1 500 m.

Table 1 - FLAC - Modelling parameters

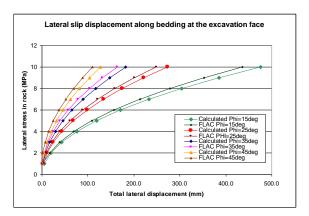| Elastic Model - Rock Properties					
Bulk Modulus (GPa)	Shear Modulus (GPa)	Rock Density (N/m^3)	Rock bed thickness (m)	Range of virgin lateral stress (MPa)	
10.67	6.40	25,000	40	1-10	
Bedding - Interface Properties					
Normal stiffness (GPa)	Shear stiffness (GPa)	Angle of friction (˚)	Cohesion (MPa)	Tension (MPa)	Dilation (˚)
10	6	15-45	0	0	0

Figure 6a - Slip length

Figure 6b - Maximum lateral displacements of strata at the bedding plane level

Figure 7 shows the magnitudes of shear slip along the weak bedding plane for various angles of friction and lateral stress of 5 MPa. As expected, lower displacements occur for higher friction along the bedding.
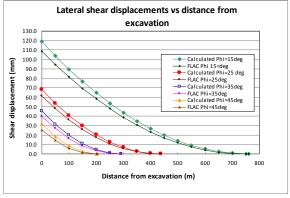

Figure 7 - Lateral shear displacement versus distance from excavation for the lateral stress of 5 MPa

DISCUSSION

Good correlation between the calculated and modelled shear displacements and bed failure length were achieved. Calculations of the lateral slip slightly overestimate the modelled results as the elastic distortion of strata above the bedding was not taken into account. The bedding failure mechanism and the prediction method of surface displacements adjacent to large excavations can be calculated as suggested. The derived calculations of strata displacements are of a simple form. This was done primarily to make the reader familiar with the proposed concepts of strata failure and movement along the bedding planes. Together with the prediction of strata movement adjacent to large excavations, land surveys should be conducted to build a database for strata movement verifications. The calculations of lateral strata movement can be very useful when protecting large surface structures such as concrete water storage dams or bridges that are very sensitive to ground movement.

CONCLUSIONS

The intention of this paper is to provide the reader with a better understanding of the ground behaviour at a shallow depth and to stimulate further research in this poorly understood topic. The origin of lateral stress at a shallow depth, the lateral stress relief adjacent to an excavation, the bedding failure mechanism and lateral displacements along failed bedding planes due to the stress relief have been explained. The described theory indicates that it is possible to use simple calculations to estimate relatively complex strata movements adjacent to large excavations within the bedded ground. The derived equations provide a simple solution to estimate the lateral ground movement without resorting to more complex numerical modelling.

Further research is underway to enable displacement calculations at any point within the strata (surface or underground) incorporating multiple bedding failure, shear distortion and stress distribution as measured underground.

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